Example 3f: High-Fidelity Generalized Method of Cells

This example problem performs analysis of a SiC/Ti-21S composite using the doubly periodic high-fidelity generalized method of cells (HFGMC) and compares the results to those of GMC. In particular, transverse strain is applied to the composite, the 26×26 circular fiber approximation RUC is employed, and the local field results in the composite are examined. HFGMC is formulated using a higher order displacement field than that employed within GMC. This provides HFGMC with normal-shear field coupling that is absent in GMC and allows HFGMC to be more accurate in terms of the local fields. In addition, while the local fields in GMC are piecewise uniform (i.e., constant within each subcell), HFGMC's local fields vary within the subcells. Thus, in HFGMC all field variables must be tracked not just once for each subcell (as in GMC), but rather at a number of integration points within each subcell. This number of integration points that MAC/GMC 4.0 employs in each subcell, along with the order of the polynomial employed to approximate the inelastic strain field in the composite, must be specified by the user. Because HFGMC employs a higher order displacement field, it requires solution for a greater number of unknowns. This, coupled with the fact that the field variables must be tracked at several integration points within each subcell, renders HFGMC significantly more computationally demanding than GMC. Thus HFGMC's improved accuracy comes at an increased computational cost over GMC. For more information on HFGMC, see the MAC/GMC 4.0 Theory Manual Section 2.1.2.

MAC/GMC Input File: **example_3f.mac**

```
MAC/GMC 4.0 Example 3f - HFGMC doubly periodic analysis
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*RUC
  MOD=12 ARCHID=13 VF=0.25 R=1. F=1 M=2
#  MOD=2 ARCHID=13 VF=0.25 R=1. F=1 M=2
*MECH
  LOP=2
  NPT=2 TI=0.,200. MAG=0.,0.02 MODE=1
*THERM
  NPT=2 TI=0.,200. TEMP=650.,650.
*SOLVER
  METHOD=1 NPT=2 TI=0.,200. STP=1.
  NLEG=5 NINTEG=11
*PRINT
  NPL=6
*MATLAB
  N=1 TIMES=200.
*XYPLOT
  FREQ=5
  MACRO=1
   NAME=example_3f X=2 Y=8
  MICRO=0
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:

Number of materials:	2	(NMATS=2)
Materials:	SiC fiber	(MATID=E)
	Ti-21S	(MATID=A)
Constitutive models:	SiC fiber: linearly elastic	(CMOD=6)
	Ti-21S matrix: Isotropic GVIPS	(CMOD=4)

3) Analysis type (***RUC**) → Repeating Unit Cell Analysis [KM_3]:

Analysis model:	Doubly periodic HFGMC	(MOD=12)
	Doubly periodic GMC	(MOD=2)
RUC architecture:	26×26 circular fiber approx., rectangular pack	(ARCHID=13)
Fiber volume fractions:	0.25	(VF=0.25)
Unit cell aspect ratio:	1.0 (square pack)	(R=1.0)
Material assignment:	SiC fiber	(F=1)
	Ti-21S matrix	(M=2)

By commenting and uncommenting the appropriate lines, HFGMC or GMC may be employed in the present example. It should be noted that the present implementation of the doubly periodic HFGMC model within MAC/GMC 4.0 requires the number of subcells in each direction to be even. If an RUC from the MAC/GMC RUC library that has an odd number of subcells in either direction is selected, an error will occur and execution will stop. For more information on HFGMC, see the MAC/GMC 4.0 Theory Manual Section 2.1.2.

4) Loading:

a) Mechanical (***MECH**) [KM_4]:

Loading option:	1	(LOP=1)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Load magnitude:	0., 0.02	(MAG=0.,0.02)
Loading mode:	strain control	(MODE=1)

b) Thermal (***THERM**) [KM_4]:

Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Temperature points:	650., 650. °C	(TEMP=650.,650.)

c) Time integration (***SOLVER**) [KM_4]:

Time integration method:	Forward Euler	(METHOD=1)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Time step sizes:	1. sec.	(STP=1.)
Order of Legendre polynomial:	5	(NLEG=5)
No. integration points per subcell:	11	(NINTEG=11)

As mentioned above, unlike GMC the local fields within HFGMC vary within each subcell. Thus, a number of integration points (NINTEG) at which to track the field variables within each subcell must be specified. Further, the inelastic strain field is approximated using Legendre polynomials. The order of these polynomials (NLEG) must also be specified. While users may employ desired values for these terms, NLEG=5 and NINTEG=11 have been shown to yield good precision in the local results. It is recommended that these values be employed unless the user is confident in altering them. For more information, see the MAC/GMC 4.0 Keywords Manual Section 4.

5) Damage and Failure: None

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level:	6	(NPL=6)

b) Matlab output data (***MATLAB**) [KM_6]:

Number of Matlab output times:	1	(N=1)
Matlab output times:	200. sec.	(TIMES=200.)

In order to display the local fields generated by the GMC and HFGMC models in the present example, the ***MATLAB** keyword has been utilized. This option generates data files containing the local fields within the composite that can be used to generate surface or "fringe" plots using the MATLAB software product. The user specifies the number of times (N) during the MAC/GMC 4.0 simulation that MATLAB output will be written, as well as the actual output times (TIMES) themselves. For more information on generating MATLAB fringe plots like those shown in this example, see the MAC/GMC Keywords Manual Section 6 and Example Problem 6c in this manual.

c) x-y plots (***XYPLOT**) [KM_6]:

Frequency:	5	(FREQ=5)
Number of macro plots:	1	(MACRO=1)
Macro plot names:	example_3f	(NAME=example_3f)
Macro plot x-y quantities:	ε_{22}, σ_{22}	(X=2 Y=8)
Number of micro plots:	0	(MICRO=0)

7) End of file keyword: (***END**)

Results

Figure 3.12 shows that the global transverse tensile response predicted by HFGMC and GMC is very similar. However, the local stress component fields plotted in Figure 3.13 (at an applied load of 0.02 transverse strain) show significant differences between the two models. First, since GMC lacks shear coupling and only normal global stresses and strains are imposed, the shear stress (σ_{23}) within the composite is zero everywhere in Figure 3.13a. In contrast, Figure 3.13b shows that HFGMC predicts significant shear stress concentrations near the fiber-matrix interface. Second, GMC predicts in-plane normal stress fields (σ_{22} and σ_{33}) that are not only uniform within each subcell, but also constant in rows (along the x_3-axis for σ_{33}) or columns (along the x_2-axis for σ_{22}) of subcells. This is another manifestation of GMC's lack of shear coupling. HFGMC, on the other hand, predicts in-plane stress fields that vary throughout the repeating unit cell with noticeable concentrations at various locations.

Figure 3.14 compares the inelastic strain component fields predicted by HFGMC and GMC at an applied load of 0.02 transverse strain. As in the stress fields, HFGMC predicts an in-plain shear concentration at the fiber-matrix interface while GMC predicts zero in-plane inelastic shear strain. Otherwise, the GMC appears to match the HFGMC inelastic strain results quite well, although HFGMC does predict higher magnitude ε_{22}^{in} and ε_{33}^{in} concentrations near the fiber-matrix interface. The improved local fields predicted by HFGMC will have the greatest effect on the predicted overall composite response when effects that depend strongly on the local fields (e.g., damage, debonding, failure) are included in the simulation.

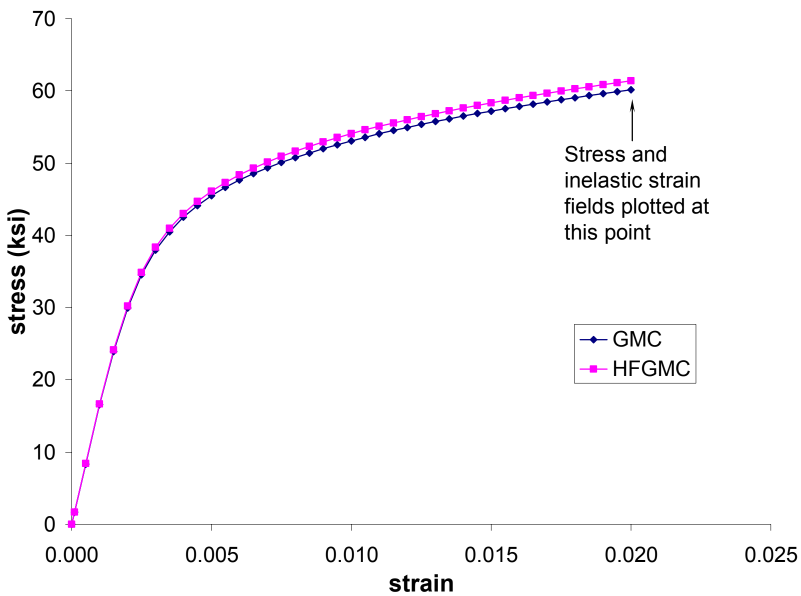

Figure 3.12 Example 3f: plot of the global transverse tensile stress-strain (σ_{22}-ε_{22}) response for a 0.25 fiber volume fraction SiC/Ti-21S composite at 650 °C as represented by a 26×26 RUC using GMC and HFGMC.

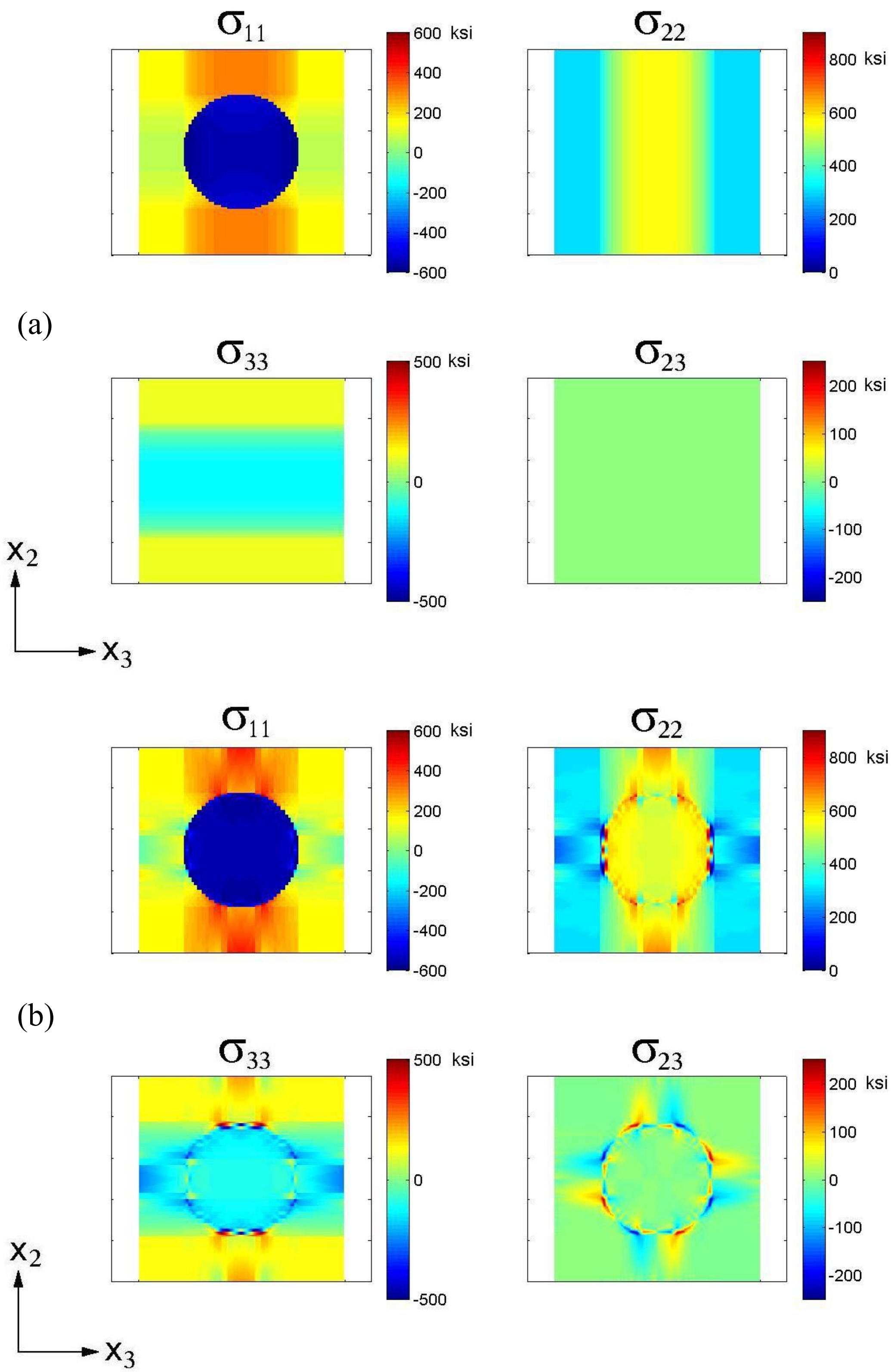

Figure 3.13 Example 3f: plots of the local stress component fields for a 0.25 fiber volume fraction SiC/Ti-21S composite at 650 °C as simulated by (a) GMC and (b) HFGMC at an applied global load of 0.02 transverse strain.

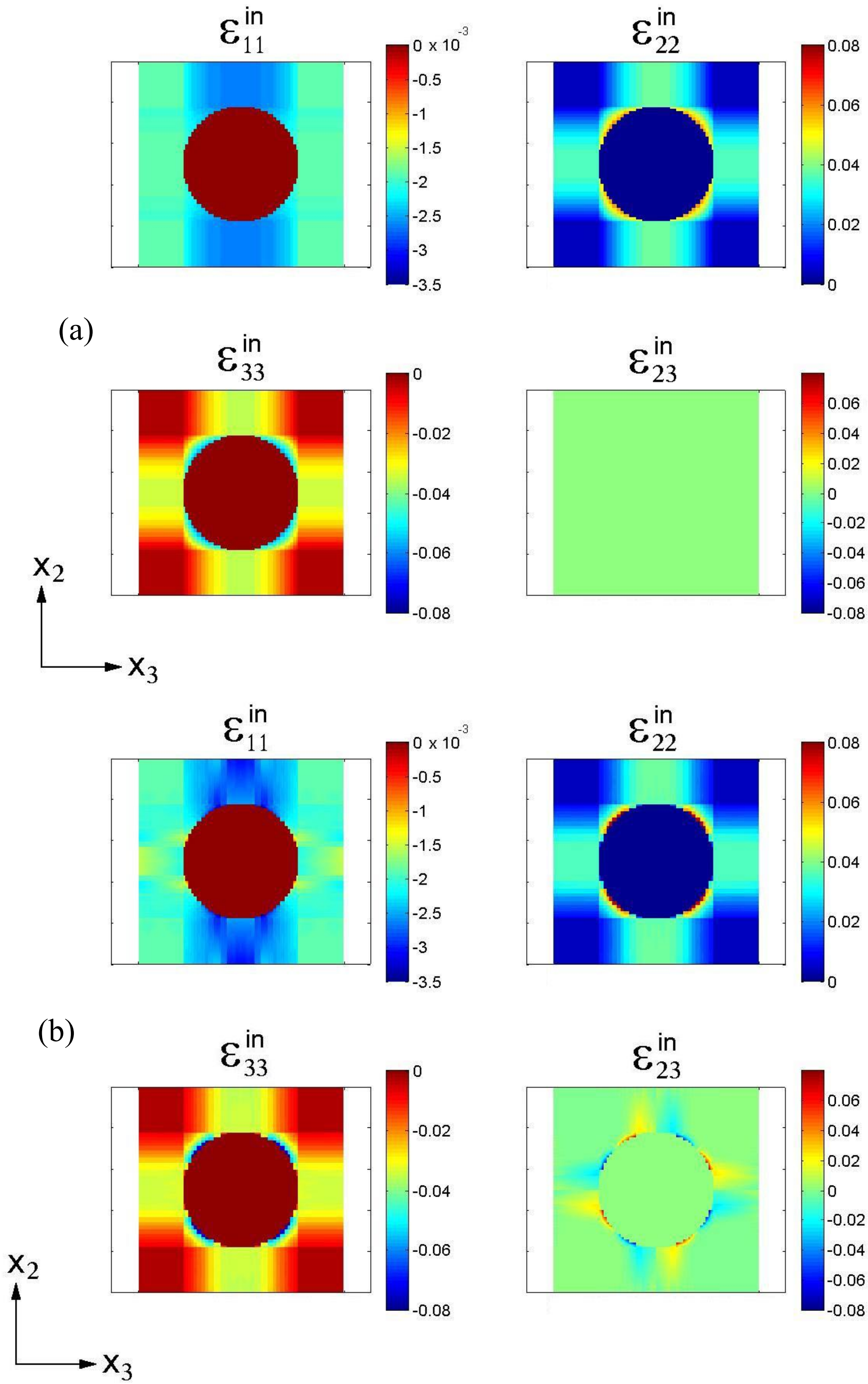

Figure 3.14 Example 3f: plots of the local inelastic strain component fields for a 0.25 fiber volume fraction SiC/Ti-21S composite at 650 °C as simulated by (a) GMC and (b) HFGMC at an applied global load of 0.02 transverse strain.